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Ultracold Neutral Plasmas

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Abstract. By photoionizing a sample of laser-cooled xenon atoms, we create ultracold neutral plasmas with initial temperatures of 1-1000 K and densities as high as $10^{10}\,\mathrm{cm}^{-3}$. The plasma is formed by the trapping of electrons by the residual positive charge that is left after some electrons initially leave the sample. We excite plasma oscillations with applied radio frequency fields and use this to monitor the expansion of the unconfined plasma. We have observed significant recombination of the plasma into Rydberg atoms (up to 20 %). At these low temperatures, the only traditional form of recombination that could be significant is three-body recombination (TBR), but we see a number of trends in direct contradiction to what one would expect from classical TBR theory.

Recent experiments conducted at the National Institute of Standards and Technology in Gaithersburg have opened a new regime of ultracold neutral plasmas with temperatures as low as a 1 K. Studies of the methods and conditions for forming the plasma[1], excitation and detection of plasma oscillations[2], dynamics of the plasma expansion[2], and collisional recombination into Rydberg atomic states[3] have demonstrated that ultracold neutral plasmas provide a powerful and flexible environment in which to test our fundamental understanding of plasmas physics.

The recipe for an ultracold neutral plasma starts with laser-cooled and trapped neutral atoms[4]. In a table-top apparatus, with a proper configuration of laser beams and magnetic fields, a few million atoms are laser cooled to approximately $10\,\mu$K. The peak density is about $2 \times 10^{10}\,\mathrm{cm}^{-3}$ and the spatial distribution of the cloud is Gaussian with an rms radius $\sigma \approx 200\,\mu$m. Many different elements can be laser cooled, and ultracold plasma experiments at NIST were performed with metastable xenon. More information on laser cooling and trapping of metastable xenon can be found in [5].

To produce the plasma, atoms are photoionized barely above threshold with a narrow-bandwidth pulsed laser. The kinetic energy of the original neutral atoms is negligible, so the energetics of the plasma is entirely determined by the photoionization process. Because of the small electron-ion mass ratio, the electrons have an initial kinetic energy (E_e) approximately equal to the difference between the photon energy and the ionization potential. E_e/k_B can be as low as the bandwidth of the ionizing laser, which is ~ 100 mK with standard pulsed dye lasers, but most studies so far have dealt with E_e/k_B between 1 and 1000 K. The initial kinetic energy for the ions is in the mK range.

Immediately after photoionization, the charge distribution is everywhere neutral. Due to the kinetic energy of the electrons, the electron cloud expands, but on this time scale the ions are essentially immobile. The resulting local charge imbalance creates an internal electric field that produces a Coulomb potential energy well for electrons. If the well never becomes deeper than E_e, all the electrons escape. If enough atoms are

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photoionized, however, only an outer shell of electrons escapes, and the well becomes deep enough to trap the rest. After the untrapped fraction has escaped, the cloud as a whole is no longer strictly neutral. Simulations show that electrons escape most easily from the edges of the spatial distribution, however, and the center of the cloud is well described as a neutral plasma.

The number of atoms ionized (N_i), and thus the density of the plasma (n), is controlled by varying the energy of the photoionizing laser pulse. Lower E_e and higher N_i lead to a greater fraction of the initially created electrons being trapped. For the coldest and densest conditions, over 90% of the electrons are confined.

For a given E_e there is a threshold number of positive ions required for trapping electrons. This threshold was demonstrated and studied in [1]. Theoretically and experimentally, it can be shown that trapping occurs when the Debye screening length, $\lambda_D = \sqrt{\varepsilon_0 k_B T_e / e^2 n}$, becomes less than the size of the sample σ. Here, ε_0 is the electric permittivity of vacuum, k_B is the Boltzmann constant, and e is the elementary charge. The electron temperature, T_e, is approximately equal to E_e/k_B [6]. An ionized gas is normally not considered a plasma unless the Debye length is smaller than the size of the system [7], so the threshold for electron trapping is also the threshold for the formation of a plasma. In our experiment, the Debye length can be as low as 500 nm, while the size of the sample is $\sigma \approx 200\,\mu$m. The condition $\lambda_D < \sigma$ for creating a plasma is thus easily fulfilled. Electron trapping can also be interpreted as a form of ambipolar diffusion.

Figure 1a shows electron signals from an ultracold neutral plasma created by photoionization at time $t = 0$. A small DC field (about 1 mV/cm) directs free electrons to a single channel electron multiplier for detection. The first peak at about 1 μs represents electrons that leave the sample and create the charge imbalance and Coulomb potential well. On a longer time scale, the plasma expands and the depth of the Coulomb well decreases, allowing the remaining electrons to leave the trap. This produces the broad peak at $\sim 25\,\mu$s. Colder and denser plasmas survive for as long as 300 μs before all the electrons escape.

It is possible to perform experiments on the system during the expansion. In [2], plasma oscillations were excited during this time interval by applying a radio frequency (rf) electric field to the plasma. The oscillations were used to map the plasma density distribution and reveal the particle dynamics and energy flow during the expansion of the ionized gas.

In the absence of a magnetic field, the frequency of plasma oscillations is given by $f_e = (1/2\pi)\sqrt{e^2 n_e / \varepsilon_0 m_e}$ [8], where n_e is the electron density and m_e is the electron mass. This expression is valid in a homogeneous medium and for excitations localized in regions of constant density in a spherically symmetric plasma. Discussions during the conference highlighted the need for a detailed analysis of the mode structure of plasma oscillations in this system, but we have so far assumed that we excite localized modes during our experiment.

Plasma oscillations with frequencies from 1 to 250 MHz have been observed, corresponding to resonant electron densities, n_r, between $1 \times 10^4\,\mathrm{cm}^{-3}$ and $8 \times 10^8\,\mathrm{cm}^{-3}$. There are small corrections to the expression for f_e due to finite temperature [9] and strong coupling [10, 11]. These were neglected in the analysis of [2], but if these effects could be observed and measured, they would provide a great deal of information on the

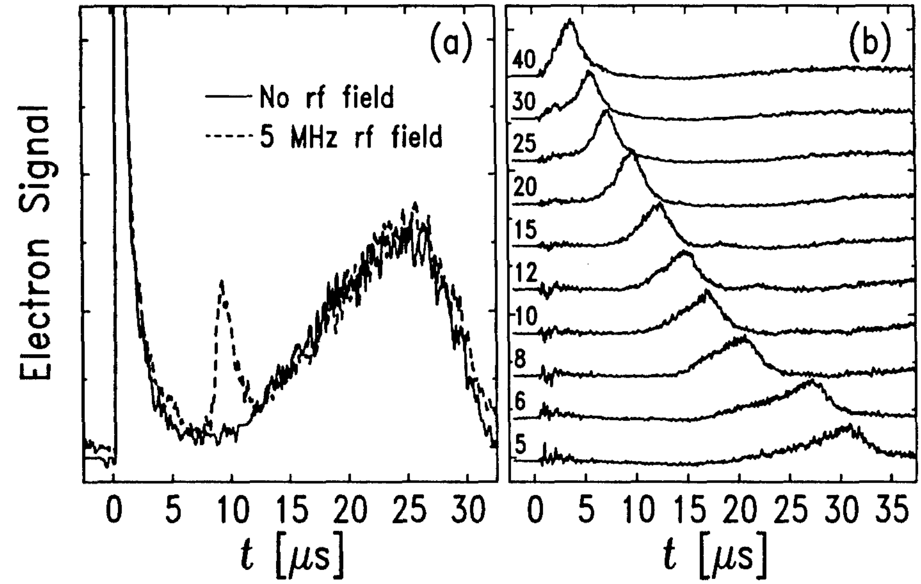

FIGURE 1. Electron signals from ultracold plasmas created by photoionization at $t = 0$. (a) 3×10^4 atoms are photoionized and $E_e/k_B = 540\,\mathrm{K}$. If an rf field is applied during the expansion, resonant excitation of plasma oscillations produces an extra peak on the electron signal. (b) 8×10^4 atoms are photoionized and $E_e/k_B = 26\,\mathrm{K}$. For each trace, the rf frequency in MHz is indicated, and the nonresonant response has been subtracted. The signals have been offset for clarity. The resonant response arrives later for lower frequency, reflecting expansion of the plasma. For 40 MHz, $n_r = 2.0 \times 10^7\,\mathrm{cm}^{-3}$, and for 5 MHz, $n_r = 3.1 \times 10^5\,\mathrm{cm}^{-3}$.

dynamics of ultracold neutral plasmas and perhaps on the physics of two-component strongly coupled systems.

The applied rf field efficiently excites plasma oscillations and pumps energy into the electron gas when the frequency is resonant with the average density in the plasma ($\bar{n}$). Collisions redistribute this energy and heat the electrons. This increases the evaporation rate of electrons out of the Coulomb well, which produces the plasma oscillation response on the electron signal (Fig. 1a). The resonant response arrives later for lower frequency (Fig. 1b) as expected because $\bar{n}$ decreases in time. With some analysis, such data implies that after a few μs the plasma expands with a constant velocity. A hydrodynamic model developed in [2] shows that the pressure of the electron gas drives the expansion, and the expansion velocity is a sensitive probe of the electron thermal energy at early times.

Recombination into Rydberg atoms in an ultracold neutral plasma was studied in [3]. At temperatures ranging from 1-1000 K, and densities from 10^5-$10^{10}\,\mathrm{cm}^{-3}$, up to 20% of the initially free charges recombine on a timescale of $100\,\mu$s. Figure 2 is an electron signal from an ultracold neutral plasma that shows the formation of Rydberg atoms. The plasma is formed as described above. After the plasma has expanded so that the ions no longer form a Coulomb well and all free electrons have escaped, the electric field is increased to 120 V/cm in $\sim 100\,\mu$s. This field can ionize Rydberg atoms bound by

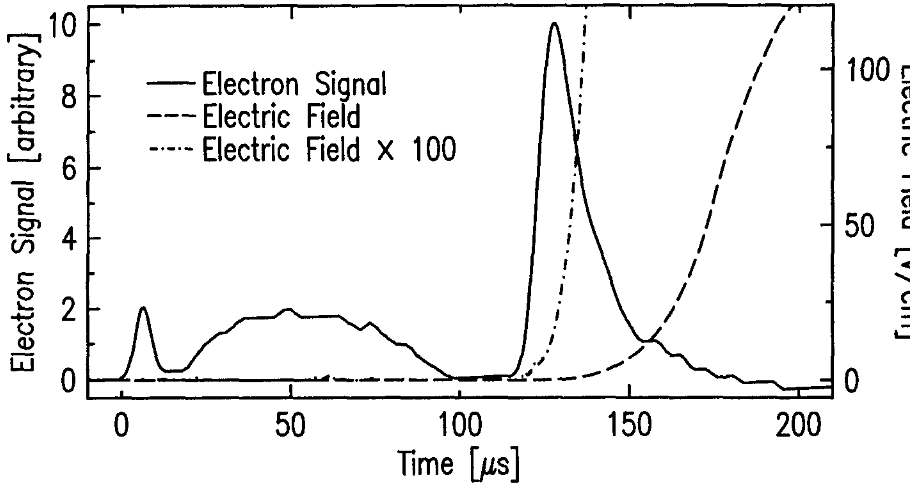

FIGURE 2. Electron signal from a plasma created by photoionizing 10^5 atoms at $t = 0$, with $E_e/k_B = 206\,K$. The first and second features represent free electrons escaping from the plasma. The third feature arises from ionization of Rydberg atoms. A 5 mV/cm field is present before the large field ramp commences at about $120\,\mu s$, and the collection and detection efficiency for the first and second features is approximately 10% of the efficiency for electrons from Rydberg atoms.

as much as 70 K, corresponding to a principle quantum number of about $p = 47$. The number of Rydberg atoms formed is inferred from the number of electrons reaching the detector, and the distribution of Rydberg atoms as a function of p is constructed from the fields at which the atoms ionize.

Figure 3 shows typical Rydberg atom data. As N_i increases, or E_e decreases, a greater fraction of charges recombine and the Rydberg atom distribution shifts toward more deeply bound levels. The integral of each curve yields the total number of Rydberg atoms formed. The expected rates for radiative recombination or dielectronic recombination are many orders of magnitude too low to account for the observed Rydberg atom formation. We turn to three-body recombination (TBR), which is expected to dominate at ultracold temperatures.

Models of population distributions in equilibrium plasmas take into account TBR, collisional ionization, and collisional and radiative population redistribution. They predict a density-independent maximum in the Rydberg atom distribution at levels bound by a few k_BT [12]. This contradicts the trend observed in this experiment toward more deeply bound levels as N_i increases or E_e decreases (Fig. 3).

Another surprising result was found by measuring Rydberg atom distributions at various times after photoionization. Most of the Rydberg atoms form $20 - 100\,\mu s$ after photoionization. By this time the plasma density has decreased three to four orders of magnitude below its initial peak value. A naive application of standard TBR theory implies that to maintain such a high recombination rate during this expansion, the temperature would have to drop below 1 mK. Evaporative cooling due to the escape of electrons from the edge of the plasma, and adiabatic cooling due to the expansion of the

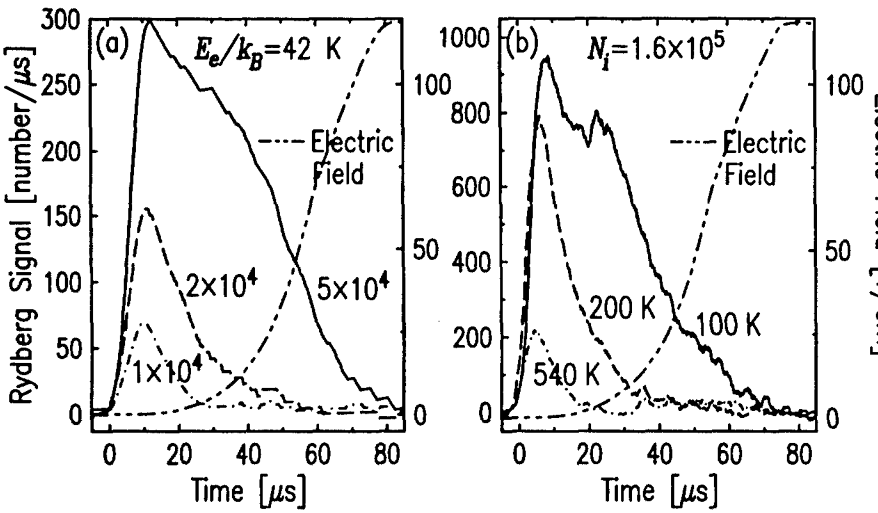

FIGURE 3. Rydberg ionization signals for various plasma conditions approximately 100 μs after photoionization. The time origin is the start of the electric field ramp. (a) Constant $E_e/k_B = 42$ K. N_i is indicated near each curve. (b) Constant $N_i = 1.6 \times 10^5$. E_e/k_B is indicated near each curve.

system could produce such extreme cooling. This is an exciting possibility. At such a low temperature the system would have an electron Coulomb coupling parameter $\Gamma_e \approx 300$. Single-component systems with such strong coupling behave as solids and minimize their potential energy by forming Wigner crystals [13]. If the cooling is less extreme, perhaps recombination in expanding ultracold plasmas proceeds through a qualitatively different mechanism than TBR. Liquid-like spatial correlations between particles should develop in the plasma as it cools to $\Gamma_e \approx 1$. Through a many-body process, spatially correlated ions and electrons could freeze out during plasma expansion, resulting in Rydberg atoms. A detailed model of the thermodynamics of the expanding plasma, or an experimental probe of the temperature of the electrons is needed to explore these possibilities.

These studies have demonstrated the fascinating behavior of ultracold neutral plasmas. The work on recombination clearly shows that much more needs to be done in order to understand this system, and also that improved diagnostics of temperature and density would be of great value. This is especially important for studying spatial correlations and looking for strong coupling in the two-component system. O'Neil at this conference and others [14] have found in simluations that electrons in ultracold neutral plasmas initially heat to $\Gamma_e \lesssim 1$ within a few plasma oscillation periods. Murillo [15] found that ions reach equilibrium in a liquid state. Currently, simulations are difficult to carry out for the longer time scales of the plasma expansion.

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